
Mapping District-Level Asbestos Exposure Risk in Java, Indonesia: Integrating Infrastructure, Demographics, and Seismic Vulnerability

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Article

Mapping District-Level Asbestos Exposure Risk in Java, Indonesia: Integrating Infrastructure, Demographics, and Seismic Vulnerability

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Abstract

(1) Background: Indonesia is one of the world's largest consumers of asbestos, with widespread use of asbestos-cement roofing across residential and public buildings. Java Island, characterized by high population density and seismic vulnerability, presents a complex risk landscape for asbestos exposure. Despite the scale of this hazard, systematic risk assessments remain limited. This study aimed to develop a district-level asbestos exposure risk map for Java by integrating asbestos roof prevalence, population density, and seismic hazard, thereby providing an evidence base for targeted public health and disaster preparedness interventions. (2) Methods: A descriptive, semi-quantitative approach was applied using secondary data from national statistics and geological hazard portals. Three variables—*asbestos roof prevalence*, *population density*, and *seismic hazard*—were categorized into five ordinal levels (very low to very high) and combined using GIS-based risk matrices to generate composite exposure risk maps. (3) Results: Of 119 districts/municipalities, 36% were classified as very high risk and 38% as high risk. Major metropolitan corridors (e.g., Greater Jakarta, Bandung) showed very high risk due to extreme population density, while several southern coastal districts exhibited elevated risk primarily due to high seismic hazard. Districts with low asbestos prevalence but high population density and seismic hazard also emerged as critical areas. (4) Conclusions: The mapping reveals that asbestos exposure risk in Java is both widespread and heterogeneous, shaped by the intersection of infrastructure, demographics, and seismic vulnerability. The resulting risk map offers a practical tool for prioritizing asbestos control, public awareness campaigns, health surveillance, and disaster risk reduction measures in Indonesia.

Keywords: asbestos exposure; risk mapping; population density; seismic hazards; Java Island

1. Introduction

Asbestos has long been recognized as a critical occupational and environmental health hazard. The International Agency for Research on Cancer classifies asbestos as a Group 1 carcinogen, signifying its definite carcinogenicity in humans [1]. Inhalation of asbestos fibers is strongly associated with chronic respiratory diseases, including asbestosis and diffuse pleural thickening, as well as malignancies such as lung cancer, malignant mesothelioma, laryngeal cancer, and ovarian cancer [2,3]. The health outcomes associated with asbestos exposure are particularly alarming due to the long latency periods of disease manifestation, the absence of curative treatment, and the typically fatal prognosis once clinical symptoms emerge. Acknowledging these grave consequences, more than 70 countries have adopted comprehensive bans on asbestos use [4]. Nonetheless, asbestos remains widely used in many developing countries, with an estimated 125 million people exposed in

occupational settings worldwide, leading to approximately 255,000 deaths annually from asbestos-related diseases (ARDs) [5,6].

Indonesia exemplifies the persistent challenges in asbestos control, as it has not yet enacted a national ban. Approximately 90% of imported raw asbestos is processed domestically into asbestos-cement products, primarily used for roofing sheets and construction materials [7]. National statistics suggest that 8–10% of Indonesian households use asbestos-cement roofs, though the prevalence is substantially higher in certain regions. In Jakarta, for example, more than half of residential buildings are estimated to have asbestos roofing [8]. This widespread usage has raised considerable public health concerns, as aging, weathering, or damage to these materials can release microscopic asbestos fibers into the air. Once inhaled, fibers persist in the lungs and pleura, leading to irreversible respiratory conditions and malignancies [9].

Despite the magnitude of this risk, asbestos-related diseases remain underrecognized in Indonesia. National health reports lack systematic data on mesothelioma or other ARDs, and official statistics are virtually absent. The first reported case of asbestos-related cancer in the country was only reported in 2019 [10]. However, recent evidence demonstrates that asbestos exposure is already contributing to Indonesia's health burden. A hospital-based case-control study showed that workers with occupational asbestos exposure had more than three times the risk of lung cancer compared to non-exposed counterparts, with the risk increasing nearly nine-fold in heavy smokers who were also exposed to asbestos. This interaction between smoking and asbestos has been well documented globally and further underscores the urgency of preventive measures [11]. The low level of awareness, coupled with weak surveillance systems, suggests that many ARD cases in Indonesia remain undiagnosed or misattributed, thereby constituting a "hidden epidemic."

The situation is further exacerbated by acute events such as natural disasters. Environmental disturbances—including unsafe renovations, demolitions, fires, and earthquakes—can dramatically increase asbestos fiber release from in-situ materials. Indonesia's location along the seismically active Pacific "Ring of Fire" makes earthquakes a particularly pressing concern [12]. The 2018 Lombok earthquake, which destroyed hundreds of thousands of homes—many roofed with asbestos—provides a salient example [13]. Inadequate hazardous waste management practices resulted in the bulldozing and open disposal of debris, a process that crushed asbestos-cement materials and dispersed fibers into nearby communities. Such post-disaster scenarios amplify asbestos exposure for residents and emergency responders alike, potentially creating long-term spikes in ARD incidence [14,15].

Despite these risks, protective policies remain limited, and public awareness of asbestos hazards in Indonesia is low. Addressing this gap requires comprehensive strategies that combine awareness campaigns, risk reduction interventions, and stronger surveillance systems. One promising approach is the development of asbestos risk maps to identify geographic hotspots of exposure and guide targeted interventions. A recent national-level study mapped asbestos exposure risk across Indonesia by integrating asbestos roof prevalence, population density, and seismic hazard. Results showed that several provinces in Java were among the highest-risk areas [12]. However, province-level mapping often masks local variability, highlighting the need for finer resolution analysis. The present study addresses this gap by developing a district-level asbestos exposure risk map for Java. This granular approach provides a more precise basis for public health authorities and disaster management agencies to raise awareness, allocate resources, and implement targeted interventions aimed at reducing asbestos-related risks in the most vulnerable communities.

2. Materials and Methods

2.1. Study Design and Setting

This study applied a descriptive, semi-quantitative design to map the risk of asbestos exposure conducted between June and September 2025. This research focused on Java Island, Indonesia, encompassing all districts and municipalities (*regency/city*) across six provinces as the units of

analysis. Java was selected given its high population density, urban growth, and widespread use of asbestos-cement products.

2.2. Data Sources and Variables

Secondary data were obtained from two official sources. First, the Indonesian Central Statistics Agency (*Badan Pusat Statistik*, BPS) provided district-level data on asbestos roofing and population density [8,16]. Asbestos data reflected the proportion of households using asbestos-cement roofing, while density was calculated from population counts and district area. Second, seismic hazard data were gathered from the Geological Disaster Mitigation Portal (*Portal Mitigasi Bencana Geologi*, PMBG), managed by the Center for Volcanology and Geological Hazard Mitigation (*Pusat Vulkanologi dan Mitigasi Bencana Geologi*, PVMBG) [17]. The PMBG portal contains spatial data on fault lines, earthquake-prone zones, and district-level seismic classifications. Together, these datasets captured three critical risk dimensions: asbestos prevalence, human exposure, and disaster vulnerability.

2.3. Risk Factor Classification

To standardize the different indicators, three variables—prevalence of asbestos roofing, population density, and seismic hazard—were stratified into five ordinal categories: very low, low, moderate, high, and very high. This approach enabled a semi-quantitative comparison across the datasets. The extent of asbestos roofing in each administrative unit was defined as the percentage of buildings constructed with asbestos-containing materials. Regions with less than 1% asbestos roof coverage were classified as very low, 1–5% as low, >5–10% as moderate, >10–20% as high, and greater than 20% as very high [12,18]. Population density, expressed as the number of inhabitants per square kilometer, was categorized according to combined references from prior studies and the Ministry of Public Works and Housing Regulation No. 2 of 2026: <50 persons/km² (very low), 51–100 (low), 101–250 (moderate), 251–400 (high), and >401 (very high) [19,20]. Seismic hazard levels were derived from the PVMBG seismic risk maps, which apply the Modified Mercalli Intensity (MMI) scale to estimate the potential intensity of earthquakes across different zones [17].

2.4. Risk Matrix Development and GIS Mapping

Two complementary risk matrices were developed to assess the potential burden of asbestos exposure. The first matrix combined asbestos roofing prevalence with population density. This approach is based on the premise that districts characterized by both extensive asbestos use and high population density are likely to face greater public health risks associated with environmental asbestos exposure.

The second matrix incorporated seismic hazard into the matrix combined asbestos roofing prevalence with population density, recognizing earthquakes as potential trigger events capable of releasing asbestos fibers through structural damage.

Each variable was assigned an ordinal score ranging from very low to very high. Composite scores were derived by averaging across variables and subsequently reclassified into five ordinal categories for spatial representation. All geospatial analyses were performed using ArcGIS 10.8. Official administrative boundary shapefiles were employed to align geospatial data.

Thematic maps were produced to illustrate: (1) asbestos roofing prevalence, (2) composite asbestos prevalence with population density, and (3) composite asbestos prevalence with population density and seismic hazard. A standardized color gradient (green = very low, red = very high) was applied to enhance interpretability. Each map included legends, province boundaries, and scale bars, and underwent peer review to ensure clarity, accuracy, and consistency.

2.5. Data Validation and Quality Assurance

To ensure reliability, several validation procedures were undertaken. First, asbestos roof prevalence figures from BPS were cross-checked against independent reports and national surveys,

which estimate an average household prevalence of ~10%. Population density data were verified against the 2020 national census, showing close alignment. For seismic hazard, PVMGB geologists provided technical guidance to confirm our interpretation of qualitative hazard categories, ensuring they matched historical earthquake records.

3. Results

Java Island comprises six provinces with a total of 119 districts and municipalities.

The distribution of asbestos use prevalence across provinces in Indonesia shows substantial geographic variation, with clear clustering of higher prevalence in urbanized and densely populated areas, particularly in DKI Jakarta and parts of West Java and East Java.

In DKI Jakarta, asbestos use prevalence is consistently high across all municipalities, ranging from 46.16% in Jakarta Selatan to 66.89% in Jakarta Utara, with the highest value observed in Kepulauan Seribu (76.66%). This indicates a widespread reliance on asbestos-containing materials, likely reflecting older housing stock, dense settlements, and legacy construction practices.

In West Java, the pattern is more heterogeneous. Several urban areas demonstrate notably high prevalence, including Depok City (45.35%), Bekasi City (33.25%), and Bogor City (30.21%). High values are also observed in peri-urban districts such as Bogor Regency (27.85%) and Bekasi Regency (21.23%), suggesting spillover effects from metropolitan expansion. In contrast, more rural districts such as Kuningan (1.91%), Majalengka (1.15%), and Ciamis (3.04%) exhibit relatively low prevalence.

Banten Province shows moderate variability, with higher prevalence in urban centers such as Tangerang City (34.90%) and South Tangerang City (18.60%), while more rural districts like Serang District (7.92%) and Serang City (6.85%) report lower levels.

In Yogyakarta, asbestos use prevalence is generally low across all districts, ranging from 1.38% in Gunungkidul to 5.37% in Yogyakarta City, indicating limited reliance on asbestos-containing materials compared to other provinces.

Central Java demonstrates a predominantly low-to-moderate prevalence pattern, with most districts reporting values below 10%. However, some notable exceptions include Cilacap (18.45%), Banyumas (10.61%), and Semarang City (28.47%), suggesting localized hotspots. Several districts report very low prevalence, such as Sukoharjo (0.98%), Karanganyar (0.96%), and Klaten (1.01%), while data gaps are present in Blora and Kudus.

In East Java, the overall prevalence is relatively low in most districts, typically below 5%, particularly in areas such as Ngawi (0.45%), Sampang (0.27%), and Jember (0.88%). However, higher prevalence is observed in several districts and urban centers, including Surabaya (32.14%), Mojokerto (9.58%), Kediri (9.51%), and Malang (8.89%), indicating uneven distribution. Industrialized and urban areas tend to exhibit higher prevalence compared to rural regions (Table 1).

Table 1. Distribution of Asbestos Use Prevalence by Province and District/City in Indonesia.

Province	Regency/City	Asbestos use prevalence
West Java	Bogor Regency	27,85
West Java	Sukabumi Regency	15,55
West Java	Cianjur Regency	11,25
West Java	Bandung Regency	5,63
West Java	Garut Regency	4,99
West Java	Tasikmalaya Regency	6,35
West Java	Ciamis Regency	3,04
West Java	Kuningan Regency	1,91
West Java	Cirebon Regency	2,77
West Java	Majalengka Regency	1,15

West Java	Sumedang Regency	2,58
West Java	Indramayu Regency	2,26
West Java	Subang Regency	3,85
West Java	Purwakarta Regency	7,73
West Java	Karawang Regency	9,15
West Java	Bekasi Regency	21,23
West Java	Bandung Barat Regency	10,44
West Java	Pangandaran Regency	20,40
West Java	Bogor City	30,21
West Java	Sukabumi City	19,22
West Java	Bandung City	12,26
West Java	Cirebon City	10,71
West Java	Bekasi City	33,25
West Java	Depok City	45,35
West Java	Cimahi City	18,68
West Java	Tasikmalaya City	4,62
West Java	Banjar City	4,91
DKI Jakarta	Kepulauan Seribu	76,66
DKI Jakarta	Jakarta Selatan	46,16
DKI Jakarta	Jakarta Timur	53,13
DKI Jakarta	Jakarta Pusat	50,13
DKI Jakarta	Jakarta Barat	52,01
DKI Jakarta	Jakarta Utara	66,89
Banten	Pandeglang District	17,09
Banten	Lebak District	14,91
Banten	Tangerang District	12,88
Banten	Serang District	7,92
Banten	Tangerang City	34,90
Banten	Cilegon City	11,36
Banten	Serang City	6,85
Banten	South Tangerang City	18,60
Yogyakarta	Kulon Progo Regency	1,49
Yogyakarta	Bantul Regency	2,28
Yogyakarta	Gunungkidul Regency	1,38
Yogyakarta	Sleman Regency	3,03
Yogyakarta	Yogyakarta City	5,37
Central Java	Cilacap District	18,45
Central Java	Banyumas District	10,61
Central Java	Purbalingga District	10,28
Central Java	Banjarnegara District	3,87
Central Java	Kebumen District	7,33
Central Java	Purworejo District	5,32
Central Java	Wonosobo District	7,88

Central Java	Magelang District	4,88
Central Java	Boyolali District	1,84
Central Java	Klaten District	1,01
Central Java	Sukoharjo District	0,98
Central Java	Wonogiri District	1,01
Central Java	Karanganyar District	0,96
Central Java	Sragen District	1,04
Central Java	Grobogan District	1,31
Central Java	Blora District	NA
Central Java	Rembang District	1,19
Central Java	Pati District	1,13
Central Java	Kudus District	NA
Central Java	Jepara District	2,29
Central Java	Demak District	6,80
Central Java	Semarang District	6,50
Central Java	Temanggung District	5,84
Central Java	Kendal District	3,72
Central Java	Batang District	2,17
Central Java	Pekalongan District	2,60
Central Java	Pemalang District	2,70
Central Java	Tegal District	4,04
Central Java	Brebes District	3,11
Central Java	Magelang City	6,35
Central Java	Surakarta City	6,87
Central Java	Salatiga City	10,12
Central Java	Semarang City	28,47
Central Java	Pekalongan City	1,22
Central Java	Tegal City	2,33
East Java	Pacitan	2,94
East Java	Ponorogo	1,36
East Java	Trenggalek	2,71
East Java	Tulungagung	2,12
East Java	Blitar	2,53
East Java	Kediri	3,43
East Java	Malang	4,10
East Java	Lumajang	3,17
East Java	Jember	0,88
East Java	Banyuwangi	2,90
East Java	Bondowoso	5,17
East Java	Situbondo	8,34
East Java	Probolinggo	2,91
East Java	Pasuruan	8,39
East Java	Sidoarjo	7,13

East Java	Mojokerto	3,83
East Java	Jombang	8,06
East Java	Nganjuk	2,71
East Java	Madiun	1,07
East Java	Magetan	0,93
East Java	Ngawi	0,45
East Java	Bojonegoro	1,35
East Java	Tuban	1,85
East Java	Lamongan	1,70
East Java	Gresik	7,92
East Java	Bangkalan	1,13
East Java	Sampang	0,27
East Java	Pamekasan	1,25
East Java	Sumenep	1,85
East Java	Kediri	9,51
East Java	Blitar	2,18
East Java	Malang	8,89
East Java	Probolinggo	2,99
East Java	Pasuruan	2,21
East Java	Mojokerto	9,58
East Java	Madiun	5,40
East Java	Surabaya	32,14
East Java	Batu	3,18

Very high levels of asbestos roof usage were identified in 15 districts/municipalities (12.6%), high in 16 (13.4%), moderate in 25 (21.0%), while the remainder fell within the low to very low categories (Figure 1). All districts/municipalities on Java exhibited high to very high population density, whereas seismic hazard varied widely from very low to high across the island.

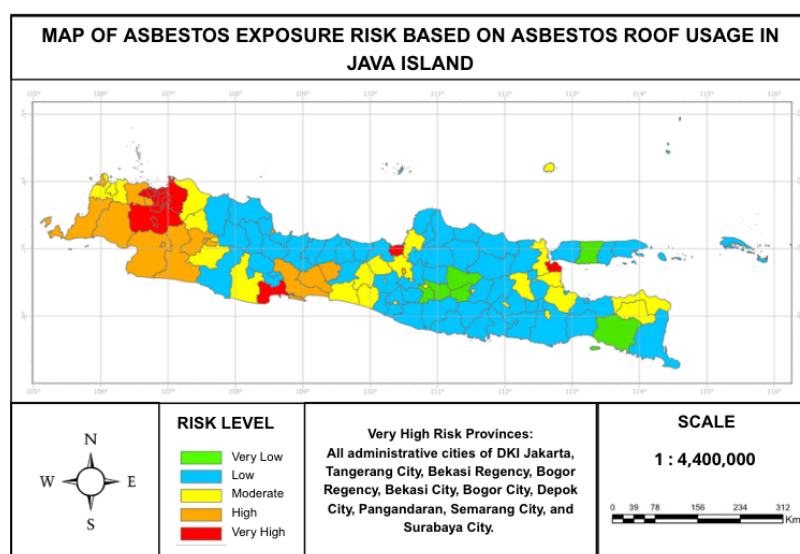


Figure 1. Map of Asbestos Exposure Risk Based on Asbestos Roof Usage in Java Island.

Figure 2 showed the map of asbestos exposure risk based on asbestos roof prevalence level and population density. Notably, more than 50% of districts and municipalities classified as very low or low in asbestos roof prevalence nevertheless demonstrated elevated asbestos exposure risk due to high to very high levels of population density.

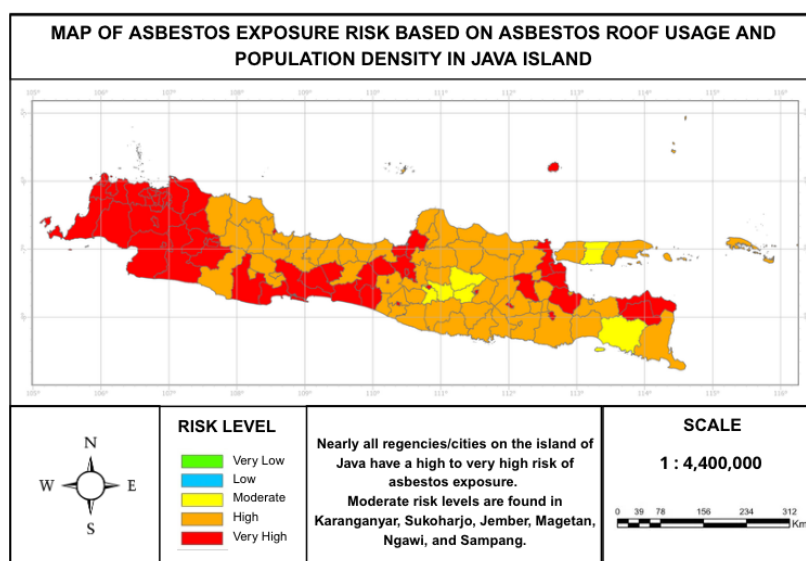


Figure 2. Map of Asbestos Exposure Risk Based on Asbestos Roof Usage and Population Density in Java Island.

A similar pattern was observed with seismic hazard: the variation across Java amplified the complexity of risk, particularly in the southern coastal regions that are prone to seismic shocks. Integrating asbestos roof prevalence, population density, and seismic hazard, the composite asbestos exposure risk distribution indicated that the majority of districts and municipalities were categorized as high to very high risk, specifically: Very high risk: 43 (36%) districts/municipalities, High risk: 45 (38%) districts/municipalities, Moderate risk: 25 (21%) districts/municipalities, Low risk: 4 (3%) districts/municipalities (Figure 3).

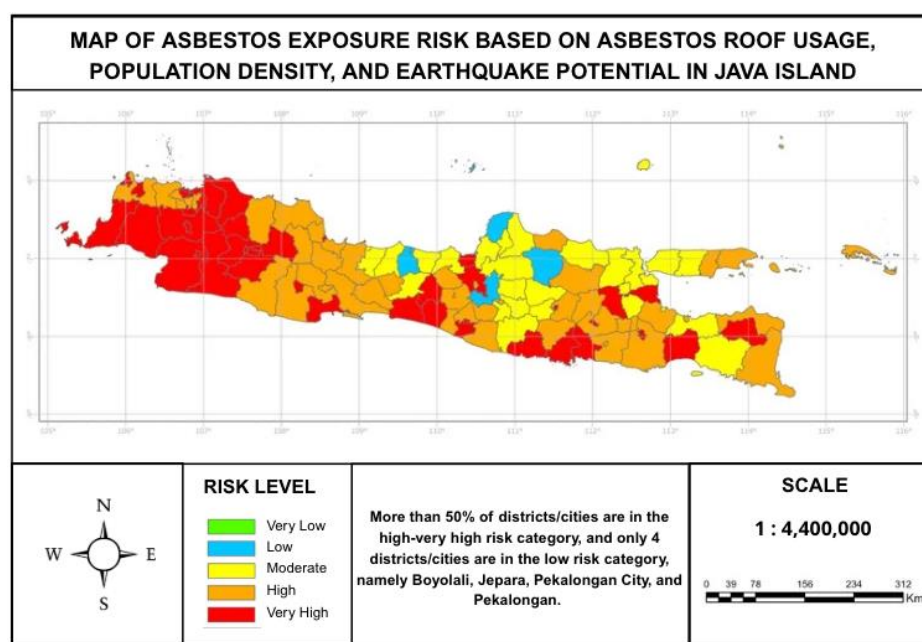


Figure 3. Map of Asbestos Exposure Risk Based on Asbestos Roof Usage, Population Density, and Earthquake Potential in Java Island.

3.1. Spatial Pattern Analysis and Priority Areas

3.1.1. Densely Populated Metropolitan Corridors

Major cities and peri-urban buffer zones in Greater Jakarta (Jabodetabek) and the Bandung metropolitan region emerge as areas of very high composite risk, despite some having only moderate to high asbestos roof prevalence. These include West Jakarta, Central Jakarta, North Jakarta, Bekasi City, Bogor City, Depok City, Bandung Regency, Bandung City, and Cimahi City. In these locations, extremely high population density substantially amplifies the risk of asbestos exposure and associated public health consequences.

3.1.2. The “Central–Southern East Java Belt” with Elevated Asbestos Roofing Prevalence

Several districts in East Java stand out for their relatively high prevalence of asbestos roofing, placing them within the very high composite risk category, even though their seismic hazard levels range from moderate to low. Districts with the highest asbestos roof percentages in this cluster include Mojokerto City ($\approx 9.6\%$), Kediri City ($\approx 9.5\%$), Malang City ($\approx 8.9\%$), Jombang ($\approx 8.1\%$), Sidoarjo ($\approx 7.1\%$), Madiun City ($\approx 5.4\%$), Yogyakarta City ($\approx 5.4\%$), and Bondowoso ($\approx 5.2\%$). The combination of higher asbestos prevalence with substantial urban or peri-urban populations drives up the composite risk score, even where earthquakes are not the dominant factor.

3.1.3. Southern Coastal Java (Earthquake-Triggered Risk)

A number of districts with low to moderate asbestos prevalence still fall into the very high composite risk category due to their high seismic hazard potential. Notable examples include Pacitan, Trenggalek, Lumajang, Bantul, Kebumen, and Cianjur. In this cluster, earthquake hazard functions as a critical trigger: seismic events can damage asbestos roofing and materials, releasing fibers widely and thereby increasing acute exposure risks for residents and emergency responders.

3.1.4. Areas with Low Asbestos Roofing Prevalence but High Population Density and Seismic Hazard

There are 35 districts and municipalities where, despite low or very low asbestos roof prevalence, composite asbestos exposure risk escalates to high or very high. This is primarily due to two amplifying factors: high to very high population density and moderate to high seismic hazard. In East Java, they include Malang, Kediri, Blitar, Banyuwangi, and Bojonegoro. Outside of East Java, similar conditions are observed in Kulon Progo, Ciamis, Pamekasan, and Sumenep. Although asbestos roof prevalence is relatively low, exposure risk is elevated due to the interaction of very high population density with moderate-to-high seismic potential.

4. Discussion

4.1. Asbestos Exposure Risk in Java in Global Context

The risk mapping results highlight a concerning convergence of asbestos use, population pressure, and seismic vulnerability in Java. Major urban centers such as Jakarta, Surabaya, and Semarang emerged as asbestos exposure hotspots, reflecting their dense populations and historically high prevalence of asbestos-cement roofing. In Jakarta, for example, over half of residential buildings are estimated to contain asbestos roofing, amplifying potential exposure for millions of inhabitants. This finding aligns with national data showing that while about 8–10% of Indonesian homes use asbestos roofs overall, highly urbanized provinces like Jakarta can exceed 50% [12]. At the same time, rural districts with extreme seismic hazard – notably Cianjur (West Java) and Pacitan (East Java) – fall into the highest risk category, despite their smaller populations. In these areas, a major earthquake could readily damage widespread asbestos materials and release fibers, elevating community exposure risk. This pattern is consistent with global observations that asbestos-related

risk is elevated both in densely populated locales with extensive asbestos use and in disaster-prone regions where infrastructure damage can abruptly liberate asbestos dust [14,21]. The present mapping underscores that Java's risk is not uniform: it is a mosaic where industrial/urban hubs and certain disaster-vulnerable districts represent "worst-case" scenarios for asbestos exposure.

In a global context, these findings reflect the ongoing shift of the asbestos burden to developing countries. Over 72 countries – primarily high-income nations – have implemented complete asbestos bans [4], and global consumption of asbestos fell sharply in the 1990s. Yet since 2000 it has plateaued at roughly 2 million metric tons per year, largely due to continued use in countries without bans [6]. Indonesia exemplifies this trend as one of the world's top asbestos importers and consumers [22]. It places Indonesian communities at a higher risk of future asbestos-related diseases, even as many Western countries begin to see the long-term benefits – and ongoing legacy challenges – of their asbestos bans [23].

4.2. *Compounded Risk During Natural Disasters*

The risks mapped in this study are compounded by the reality that Indonesia is a disaster-prone country. Natural disasters – especially earthquakes – can acutely exacerbate asbestos exposure. Indonesia's location on the seismically active Pacific "Ring of Fire" means that Java and other islands regularly experience earthquakes. When a major tremor strikes an area with many asbestos-containing structures, the shaking and collapse can pulverize asbestos materials, releasing clouds of microscopic fibers into the environment [15]. This scenario is not hypothetical; the 2018 Lombok earthquake vividly demonstrated the danger. The quake destroyed hundreds of thousands of homes, roughly a quarter of which had asbestos roofs, immediately creating vast amounts of friable asbestos debris [13].

Java faces a similar threat. The Cianjur earthquake of 2022 (West Java) and many smaller tremors serve as reminders that what happened in Lombok could happen on Indonesia's most populous island. Cianjur, identified as a top-risk district in our map, saw tens of thousands of structures damaged by a 5.6 magnitude quake; many of these structures likely contained asbestos given the region's construction profile [24]. If a larger earthquake were to strike Jakarta or other high-risk Java locales, the presence of so much asbestos in roofing could create a public health emergency with airborne fibers on a mass scale. Even historical events abroad underscore this risk: studies of the 1995 Kobe (Hanshin) earthquake in Japan found that debris from collapsed asbestos-containing buildings led to air fiber concentrations well above safe limits, proving the deadly potential of such disasters [15,25]. Therefore, it is paramount that disaster management plans in Indonesia integrate asbestos risk mitigation.

4.3. *International Comparisons: Asbestos Bans and Risk Mapping Strategies*

Many countries that have confronted asbestos hazards have implemented aggressive policies to map, mitigate, and ultimately eliminate exposure risks. Japan, for example, experienced a large-scale asbestos health crisis in the 2000s (the so-called "Kubota shock" in which residents living near an asbestos factory developed mesothelioma). In response, Japan progressively tightened regulations, culminating in a complete ban on asbestos by 2012 [6,26].

South Korea similarly banned asbestos (brown and blue asbestos in 2000, and chrysotile in 2009) and then launched comprehensive abatement programs [27]. A notable example is the Seoul Metropolitan Government's asbestos control initiative, which systematically surveyed and mapped asbestos presence in public buildings city-wide. By 2014, Seoul had inspected over 2,000 public facilities (including schools, hospitals, and subway stations) for asbestos, created an "asbestos map" identifying which buildings contained the material, and publicly disclosed the results [27]. Based on these risk maps, authorities prioritized high-exposure sites for removal of asbestos or sealed treatment, and enforced strict maintenance protocols in others. This proactive mapping and transparent risk communication helped reassure the public and guided resource allocation for asbestos removal in South Korea's capital.

Australia has gone further to integrate risk mapping into its asbestos eradication strategy. Australia banned asbestos in 2003 and established a dedicated national agency (the Asbestos Safety and Eradication Agency) to coordinate policy [28]. A key tool developed is the National Residential Asbestos Heatmap, a predictive GIS model that estimates the likelihood of asbestos presence in homes across different suburbs and regions [29]. This heatmap (updated regularly with new data) allows Australian authorities to target public awareness campaigns and inspections to areas with older housing stock or known asbestos use in construction.

4.4. Recommendations for Mitigation and Intervention

Given the findings of this study and the lessons from global best practices, concerted action is required to mitigate asbestos exposure risk in Indonesia. Key recommendations include: Targeted Public Awareness Campaigns: Increasing community awareness is crucial, especially in the identified high-risk zones. Strengthening Surveillance and Health Systems: A robust health surveillance system for asbestos-related diseases is needed. Integration of Asbestos Management into Disaster Response: As discussed, natural disasters pose a severe asbestos release threat in Indonesia. Therefore, disaster management protocols at both national (BNPB) and regional (BPBD) levels should be updated to include asbestos risk mitigation. Policy Reform and Pilot Asbestos Replacement Programs: On the policy front, Indonesia should move toward eventually phasing out asbestos use. Utilizing the Risk Map for Decision-Making: The asbestos exposure risk map developed by this study is an invaluable tool that should be fully leveraged by policymakers, health officials, and disaster management authorities. It allows for evidence-based targeting of interventions. For instance, districts categorized as highest risk (due to the confluence of heavy asbestos use, high population density, and seismic hazard) can be prioritized for the interventions listed above – be it awareness campaigns, medical surveillance, disaster prep, or roof replacement programs. By overlaying this map with data such as health facility locations, population demographics, or earthquake fault lines, officials can refine their strategies (for example, identifying which healthcare centers need capacity building for mesothelioma diagnosis, or which community centers could serve as hubs for asbestos education). The map can also be updated over time if new data emerge (e.g. if some districts eliminate asbestos use or if population patterns change).

5. Conclusions

The mapping study in Java reveals a pattern of asbestos risk that mirrors global and regional trends, and it rings an alarm for Indonesia's public health trajectory. Without intervention, urban centers with pervasive asbestos use and vulnerable rural districts could face a rise in asbestosis, lung cancer, and mesothelioma cases in the coming decades – a scenario made more likely and more acute by the ever-present threat of earthquakes releasing asbestos fibers into the environment.

6. Patents

The authors acknowledge that there are three map that has been formally registered for copyright with the Directorate General of Intellectual Property (DGIP), Indonesia, Map of Asbestos Exposure Risk Based on Asbestos Roof Usage in Java Island used in this study as Figure 1 under registration number EC002025157010. Map of Asbestos Exposure Risk Based on Asbestos Roof Usage and Population Density in Java Island as Figure 2 under registration number EC002025157011. Map of Asbestos Exposure Risk Based on Asbestos Roof Usage, Population Density, and Earthquake Potential in Java Island as Figure 3 under registration number EC002025157024.

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Abbreviations

The following abbreviations are used in this manuscript:

ARDs	Asbestos Related Diseases
BPS	Badan Pusat Statistik
PBMG	Portal Mitigasi Bencana Geologi

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